ANALYSIS OF SURFACE CHARGING FOR A CANDIDATE SOLAR SAIL MISSION USING NASCAP-2K

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Overview

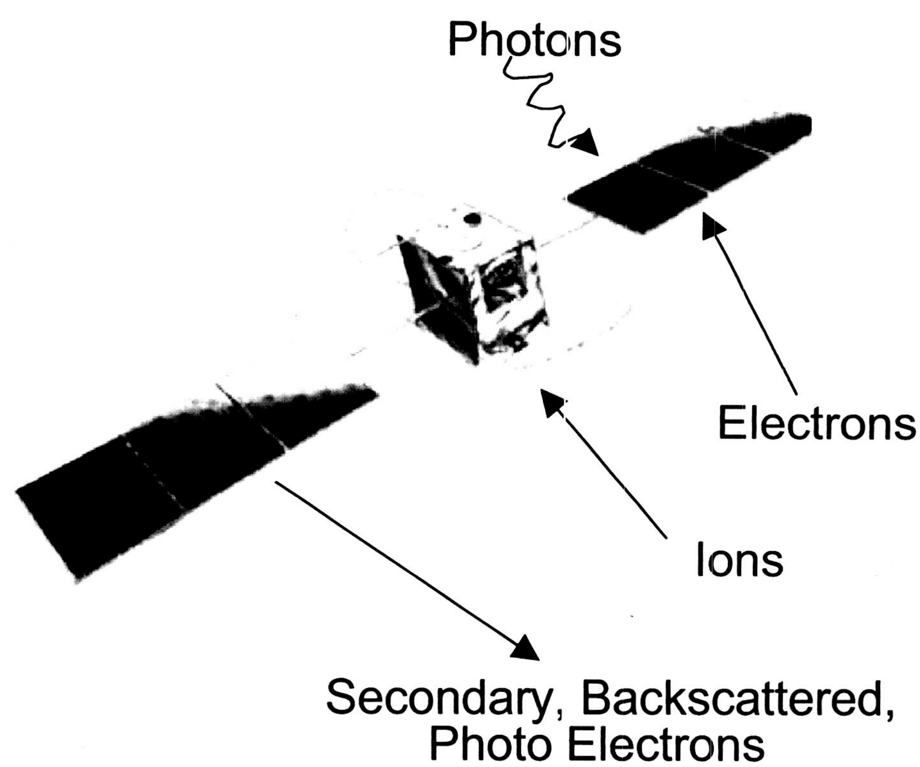
- Introduction
- Environment
- 1 AU
- 0.5 AU
- GEO
- Conclusion

Introduction

The characterization of the electromagnetic interaction for a solar sail in the solar wind environment, and identification of viable charging mitigation strategies, is a critical solar sail mission design task, as spacecraft charging has important implications both for science applications and for sail lifetime. To that end, we have performed surface charging calculations of a candidate 150-meter-class solar sail spacecraft for the 0.5 AU solar polar orbit and a 1.0 AU L1 orbit. We construct a model of the spacecraft with candidate materials having appropriate electrical properties using Object Toolkit and perform the spacecraft charging analysis using NASCAP-2k, the NASA/AFRL sponsored spacecraft charging analysis tool. We use nominal and atypical solar wind environments appropriate for the 0.5 AU and 1.0 AU missions to establish current collection of solar wind ions and electrons. In addition, we include a geostationary orbit case to demonstrate a bounding example of extreme (negative) charging of a solar sail spacecraft in the geostationary orbit environment. Results from the charging analysis demonstrate that minimal differential potentials (and resulting threat of electrostatic discharge) occur when the spacecraft is constructed entirely of conducting materials, as expected. Examples with dielectric materials exposed to the space environment exhibit differential potentials ranging from a few volts to extreme potentials in the kilovolt range.

What is Spacecraft Surface Charging?

- Spacecraft potential rapidly changes until net current is zero.
- $I_{net} = -I_e + I_{sec} + I_{back} + I_{photo} + I_{ion}$
- More slowly, each surface charges until its net current is zero.
- Differential potentials can cause discharges.



Solar Wind Charging Environment

- Protons are beaming from sun direction

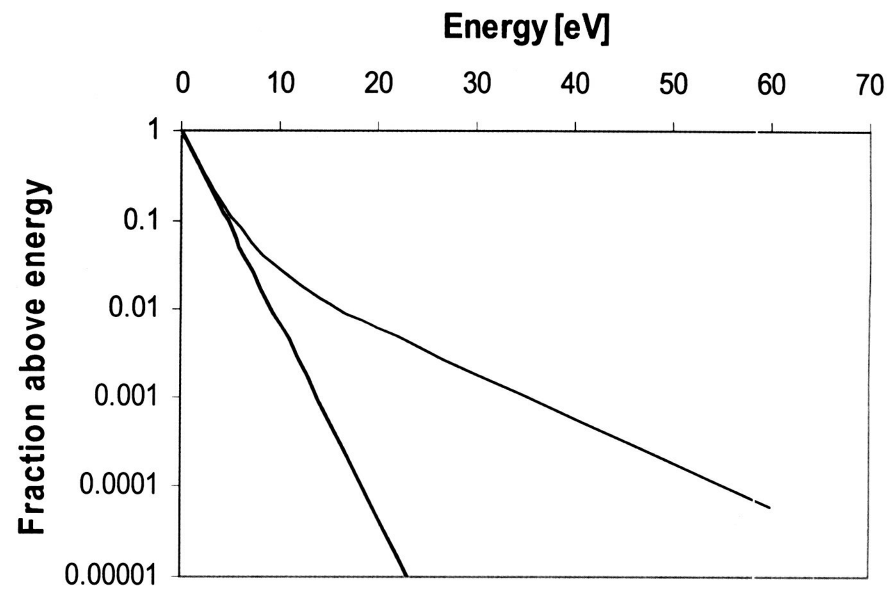
  v ~ 430 km/s

  E ~ 1 keV
- Electrons are isotropic
- At 1 AU:

  Plasma Density ~ 10^7 m^{-3}

  Plasma Temperature ~ 15 eV

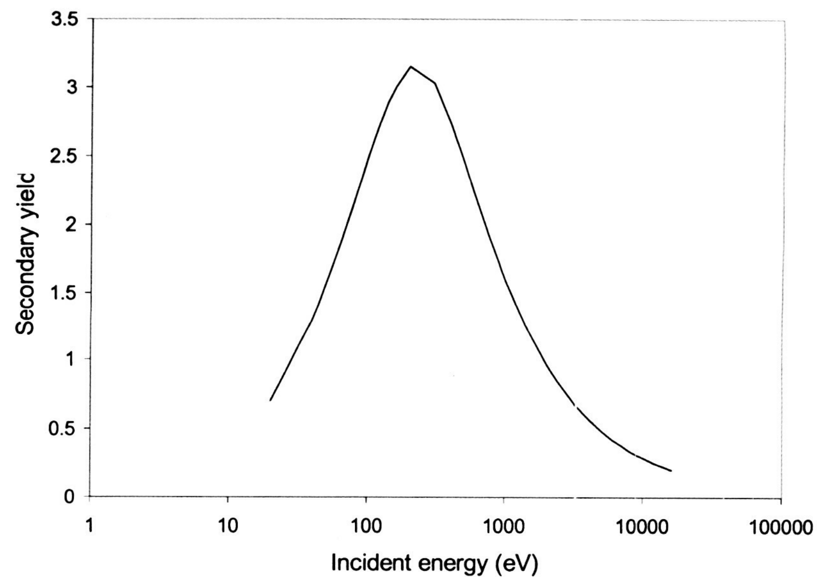
  Debye Length ~ 10 m
- Effective photoemission decreases with potential slower than 2 eV Maxwellian
- In inner solar system, photoemission dominates currents.
- Spacecraft charges positively until escaping energetic photoelectrons balance incident electrons.



Upper curve is realistic photoelectron spectrum.
Lower curve is 2 eV Maxwellian, as used in NASCAP/GEO.

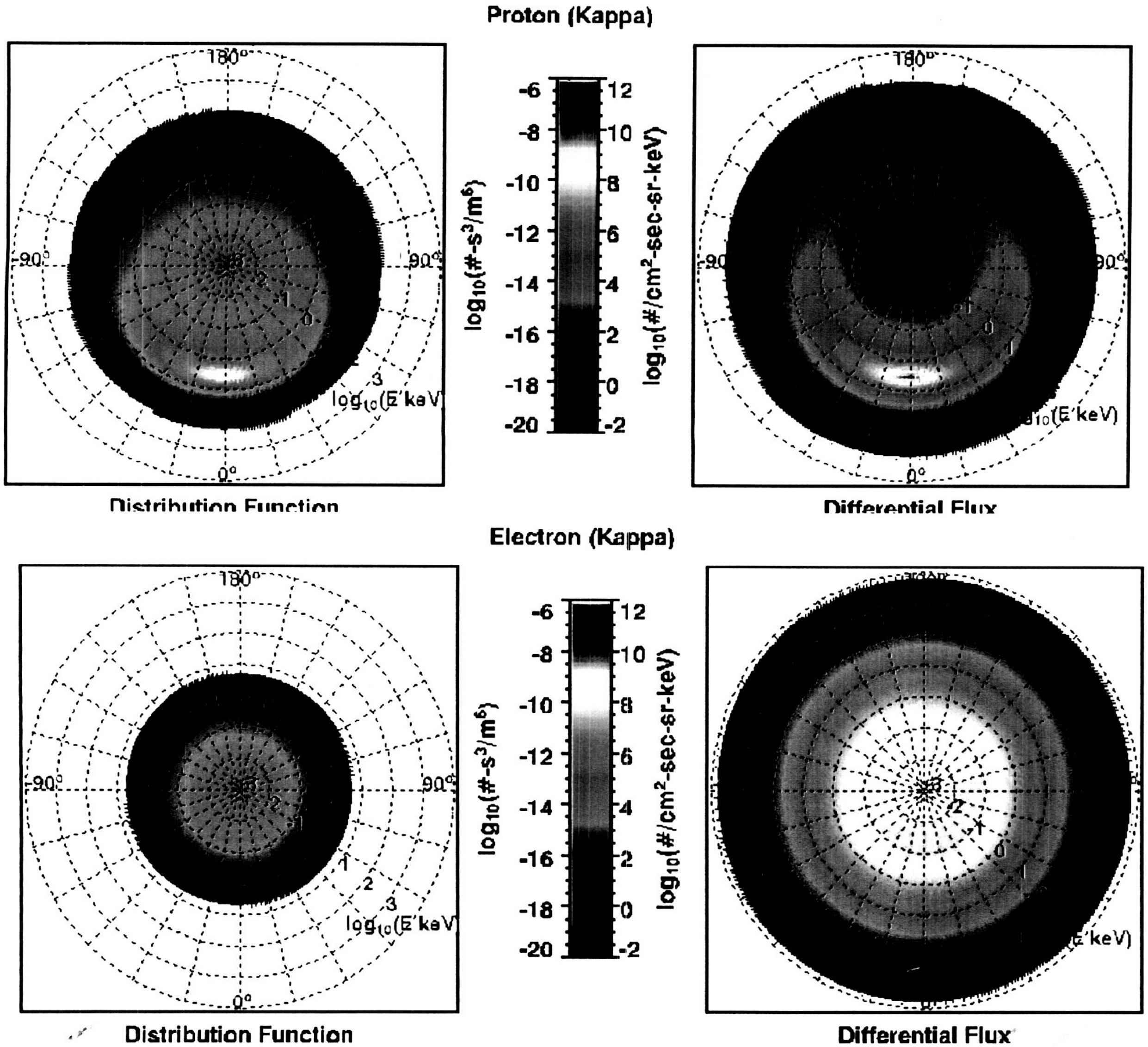
High Temperature Solar Wind Environment Can be Non-Charging

- For a 50 eV Maxwellian plasma, the average secondary yield is > 1 for a net positive current to the anti-sun side of a sail.



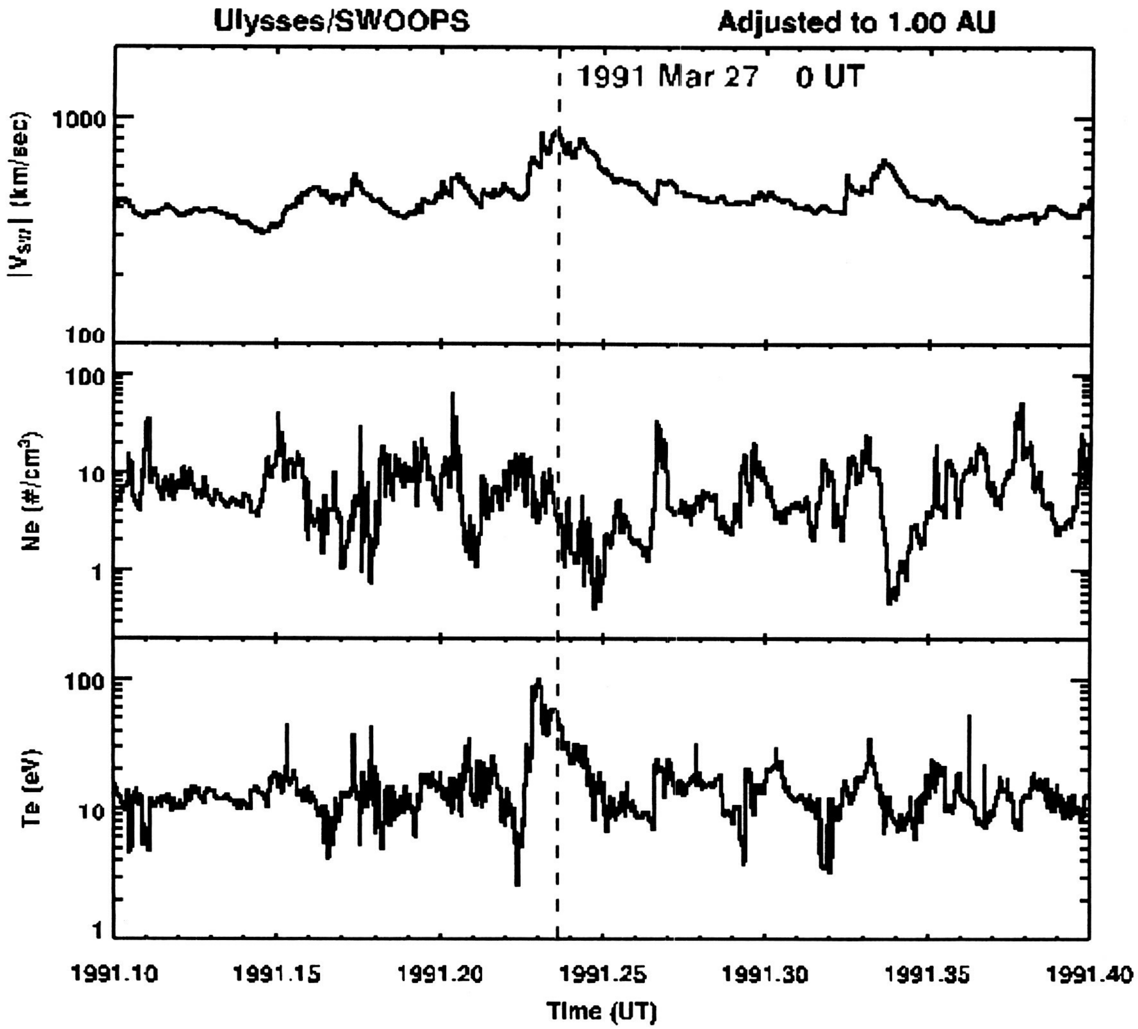
$$\mathrm{Flux}_{net} = \int_0^{\infty} \mathrm{Flux}_{incident}(E)\left[-1 + Y_{secondary}(E) + Y_{backscatter}(E)\right] dE > 0$$

Kappa Distributions



Kappa distribution fits to the data for proton and electron flux. The proton flux is anisotropic with the bulk of the flux in a narrow range of angles which will impact the illuminated side of the solar sail. Kappa distributions predict a small flux of protons to the back side of the sail. In comparison, the electron flux for the same energy range is nearly isotropic in the modeled distributions so electrons will impact both sides of the solar sail.

Ulysses Data



•The Solar Wind observations Over the Poles of the Sun (SWOOPS) instrument [*Bame et al.*, 1992] on-board the Ulysses spacecraft provides the low energy electron and ion component of the solar wind used to define the charging environments for the solar sail. Data is scaled from the spacecraft location which varies from 1.0 to 5.4 AU to the solar sail mission distances of 0.5 and 1.0 AU.

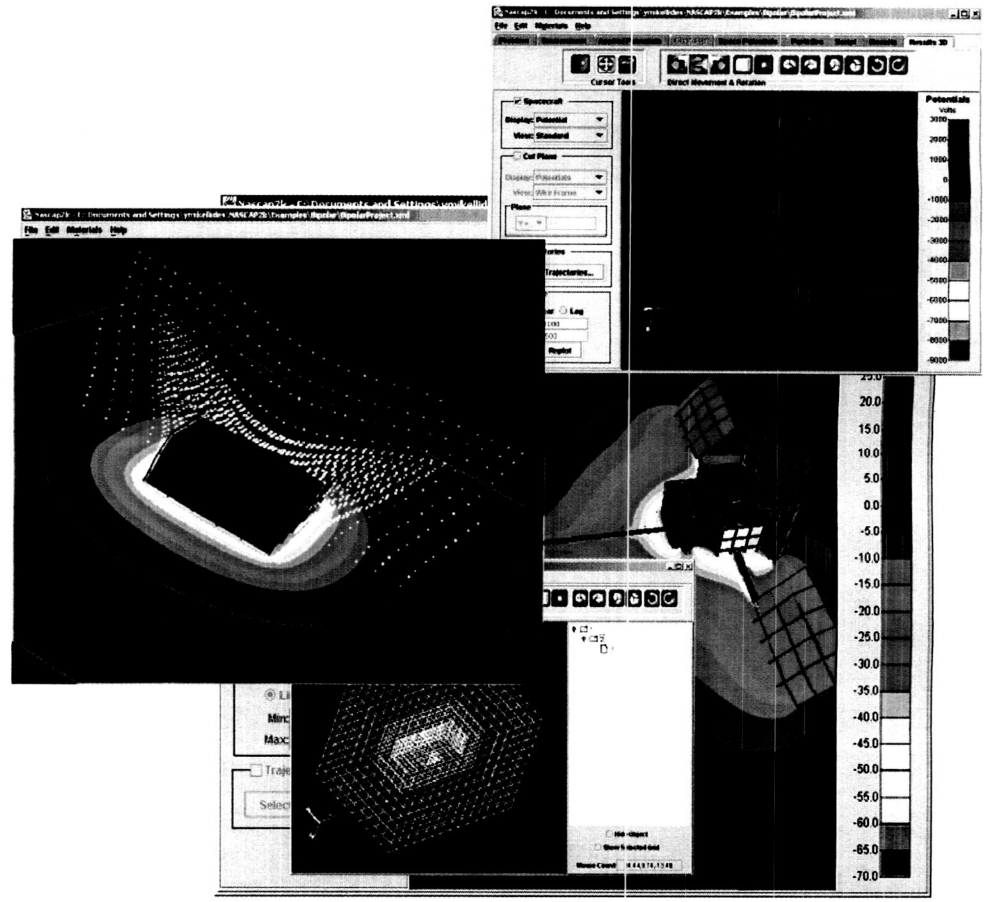
•An environment with excess electrons impacting the backside predicts the possibility of negative potentials.

•Electron velocity, density, and temperature for the Ulysses SWOOPS data is scaled to 1 AU for the first third of 1991 (only the density and temperature values require scaling, velocity is independent of radial distance from the Sun).

•The red line marks the March 27, 1991 period selected for use as an "Extreme" charging environment for the 1AU and ½ AU cases. Solar wind plasma velocity is high during this event (~863 km/sec), with elevated electron temperatures suggesting an opportunity to collect large currents from the plasma environment.

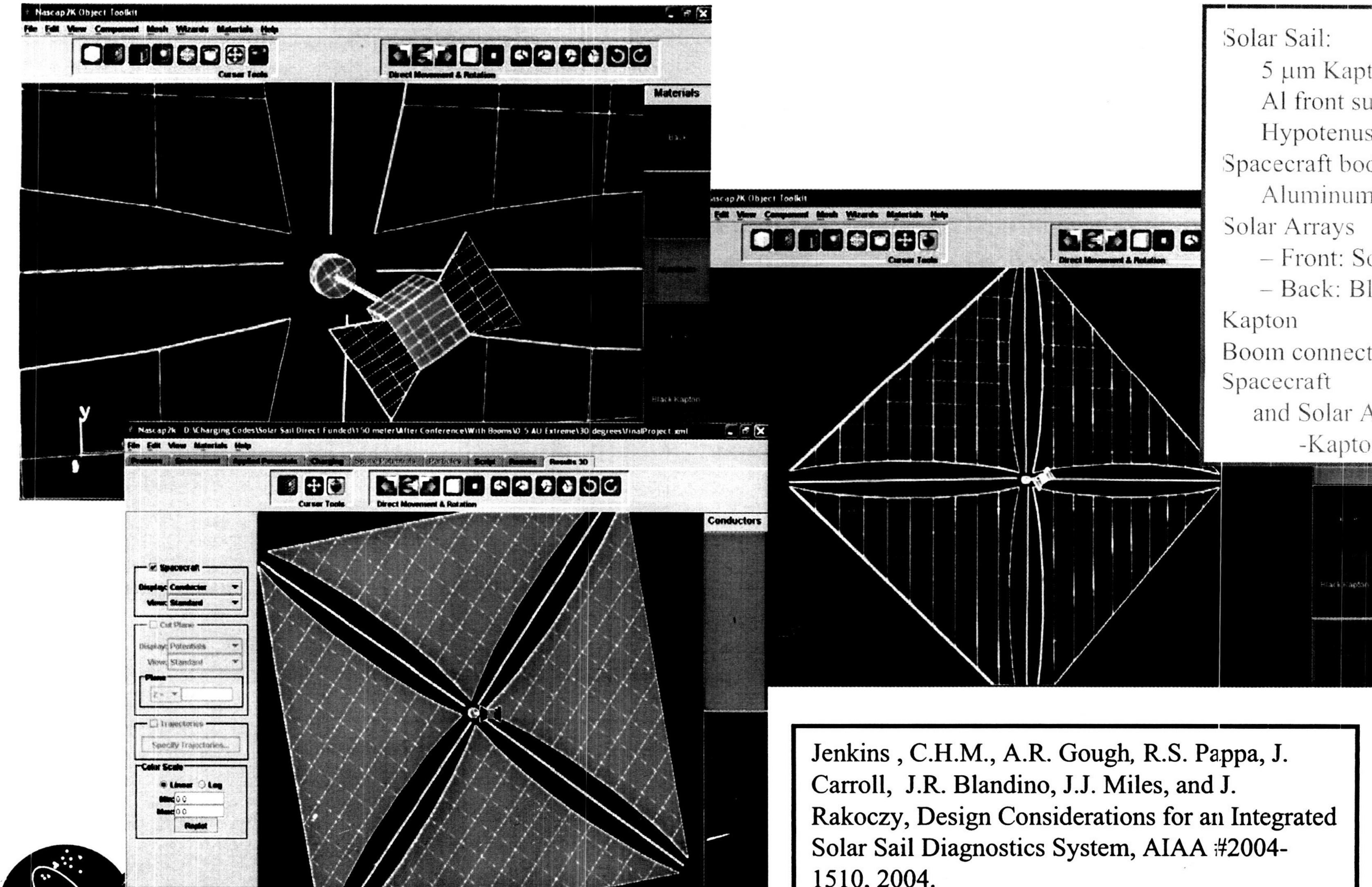
Nascap-2K
NASA & **A**ir Force **S**pacecraft **C**harging **A**nalyzer **P**rogram 2000

- Tenuous Plasma
  - Geosynchronous surface charging
  - Solar Wind surface charging
  - Potentials and Fields
  - Particle Tracking
- Dense Plasma
  - External Potentials
    - Analytic Space Charge
    - Hybrid Space Charge
  - Current Collection
  - Auroral Charging
  - PIC
- Uses BEM (boundary element method) of solving equations



M. J. Mandell, V. A. Davis, B. M. Gardner, I. G. Mikellides, D. L. Cooke, J. Minor, NASCAP-2K, An Overview, Proceedings of the 8th Spacecraft Charging Technology Conference, 2003.

150 m Model



Solar Sail:
- 5 µm Kapton
- Al front surface
- Hypotenuse = 150 m

Spacecraft body:
- Aluminum

Solar Arrays
- – Front: Solar Cells
- – Back: Black Kapton

Boom connecting Spacecraft
- and Solar Array craft -Kapton

Jenkins , C.H.M., A.R. Gough, R.S. Pappa, J. Carroll, J.R. Blandino, J.J. Miles, and J. Rakoczy, Design Considerations for an Integrated Solar Sail Diagnostics System, AIAA #2004-1510, 2004.

Charging Analyses

	Solar Wind: 1 AU	Solar Wind: 0.5 AU	Geosynchronous
150 m	1. Sun/plasma incident normal to sail front (env 1 & 2) 2. Sun/plasma incident 30° from normal (env 1& 2) 3. Sun/plamsa incident 55° from normal (env 1 & 2) 4. Sun/plasma incident 30° from normal with conductive sail backing (env 1)	1. Sun/plasma incident normal to sail front (env 1 & 2) 2. Sun/plasma incident 30° from normal (env 1& 2) 3. Sun/plamsa incident 55° from normal (env 1 & 2) 4. Sun/plasma incident 30° from normal with conductive sail backing (env 1)	1. Sun/plasma incident 30° from normal 2. Sun/plamsa incident 55° from normal 3. Loss of attitude control (-normal)

a= normal, b=30° from normal, c=55° from normal

Charging Environments

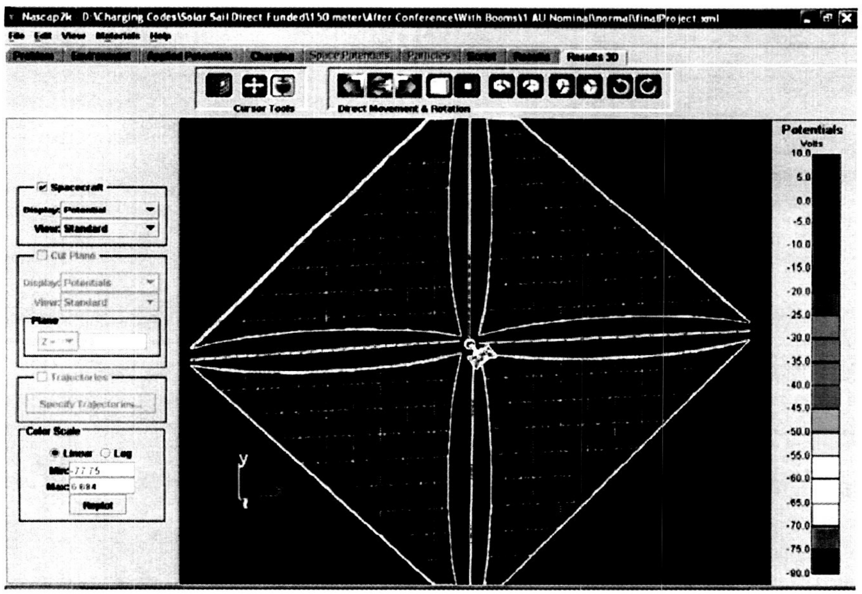
	1 AU Environment 1*	1 AU Environment 2ξ	½ AU Environment 1*	½ AU Environment 2ξ	Geo worst caseζ
Electron density	12.8 cm^{-3}	3.28 cm^{-3}	4.27 cm^{-3}	13.1 cm^{-3}	1.12 cm^{-3}
Electron temperature	11.13 eV	55.4 eV	10.6 eV	68.2 eV	12 keV
Ion velocity	327 km/s	863 km/s	702 km/s	863 km/s	
Ion Energy / temp	558.2 eV	3888 eV	2573 eV	3888 eV	29.5 keV
Ion density					0.236 cm^{-3}
Debye length	7 m	31 m	6 m	17 m	770 m
Sun	Intensity = 1, Angle incident: normal, 30° and 55 ° from sail normal	Intensity = 1, Angle incident: normal, 30° and 55 ° from sail normal	Intensity = 4, Angle incident: normal, 30° and 55 ° from sail normal	Intensity = 4, Angle incident: normal, 30° and 55 ° from sail normal	Intensity = 1, Angle incident: 30° and 55 ° from sail normal

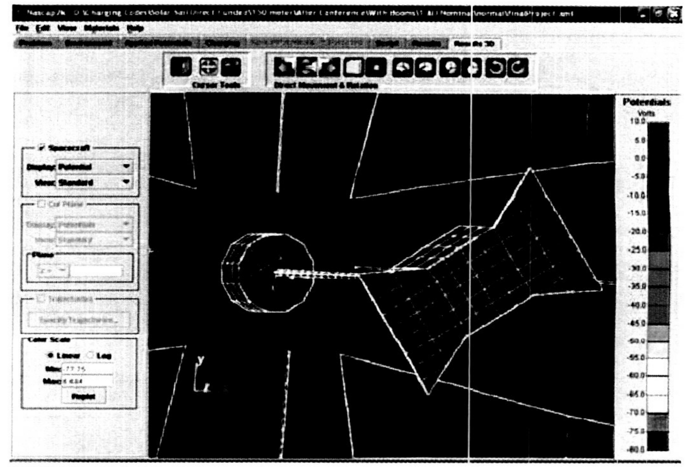
*Feldman, et al., *Plasma and Magnetic Fields From the Sun,in the Solar Output and Its Variation*, Table 4, 1977.

ξ Bame, S.J., D.J. McComas, B.L. Barraclough, J.L. Phillips, K.J. Sofaly, J.C. Chavez, B.E. Goldstein, R.K. Sakurai, The Ulysses Solar Wind Plasma Experiment, Astronomy and Astrophysics, Supplement Series, Ulysses Instruments Special Issue, Vol. 92, 237 – 265, 1992.

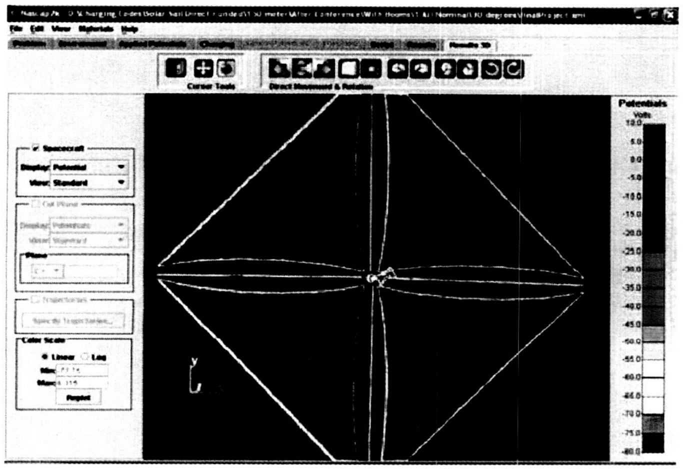
ζ C. K. Purvis, H. B. Garrett, A. C. Whittlesey, N. J. Stevens, *Design Guidelines for Assessing and Controlling Spacecraft Charging Effects*, NASA TP 2361, 1984.

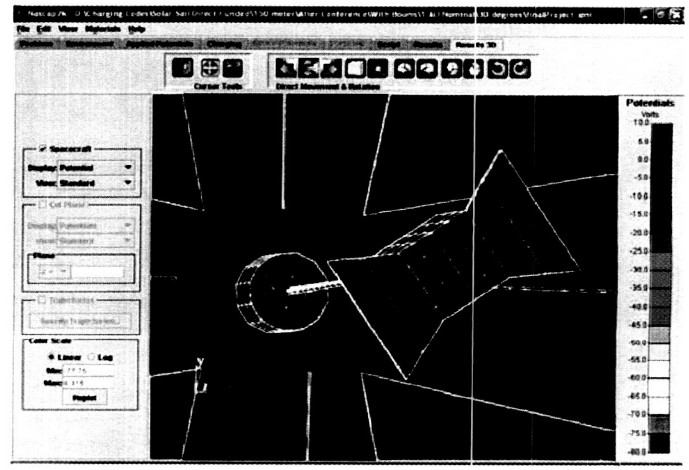
1 AU Environment 1, Insulating Back - normal

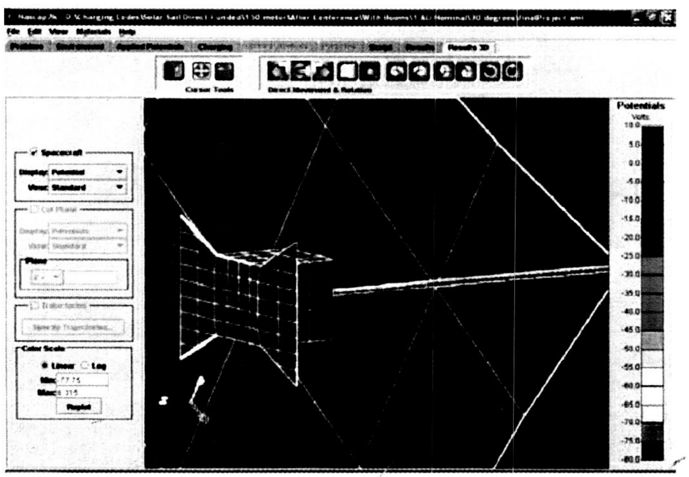


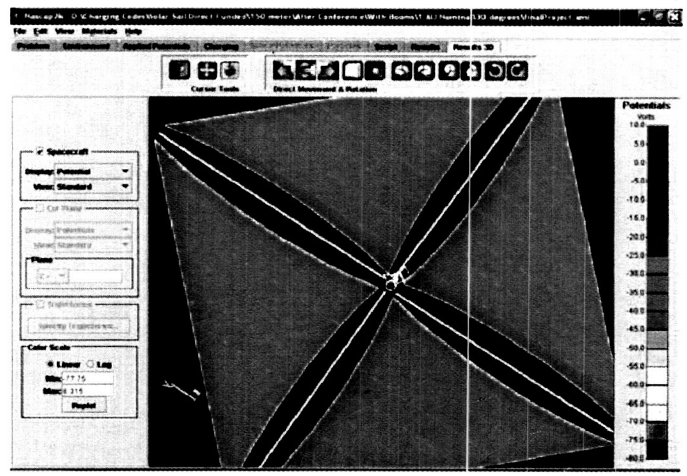


1 AU Environment 1, Insulating Back – 30 degrees

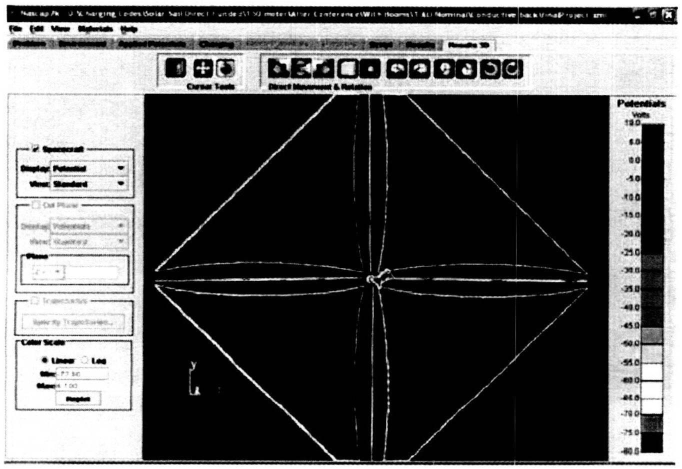


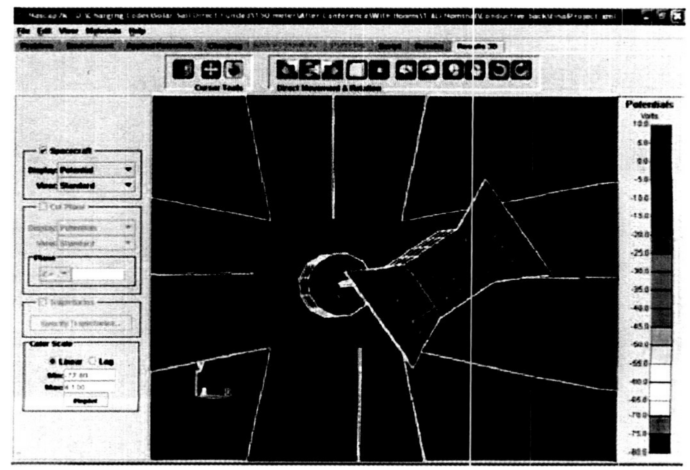


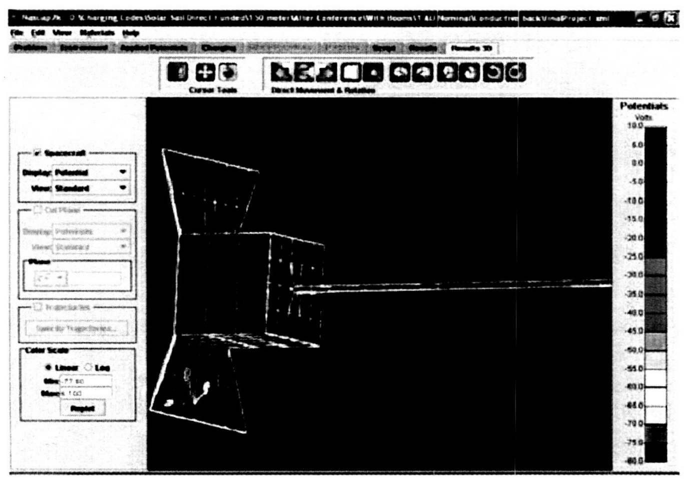


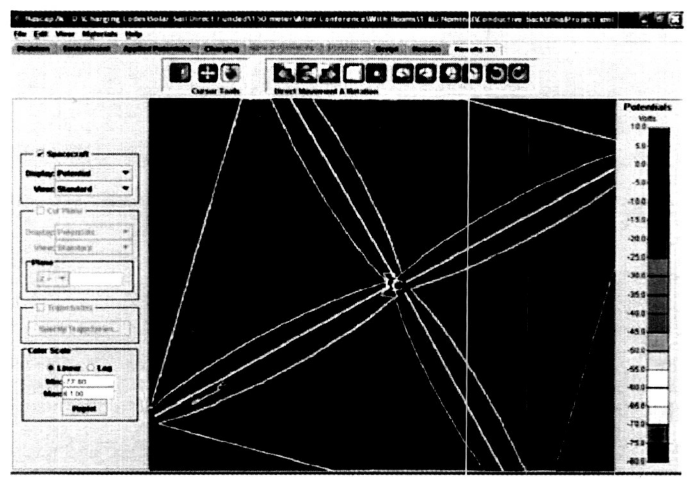


1 AU Environment 1, Conducting Back – 30 degrees

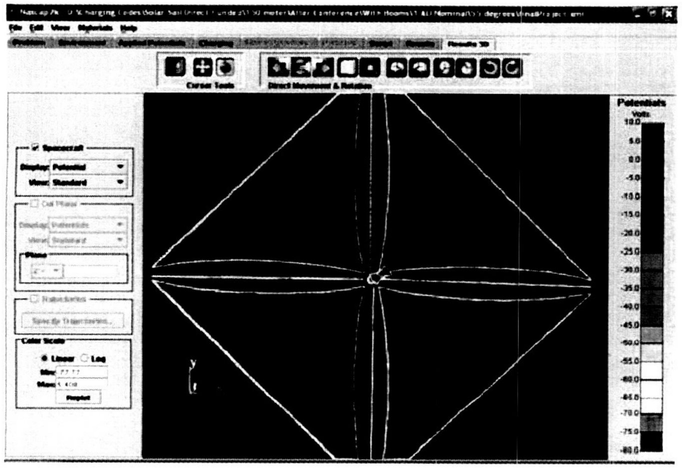


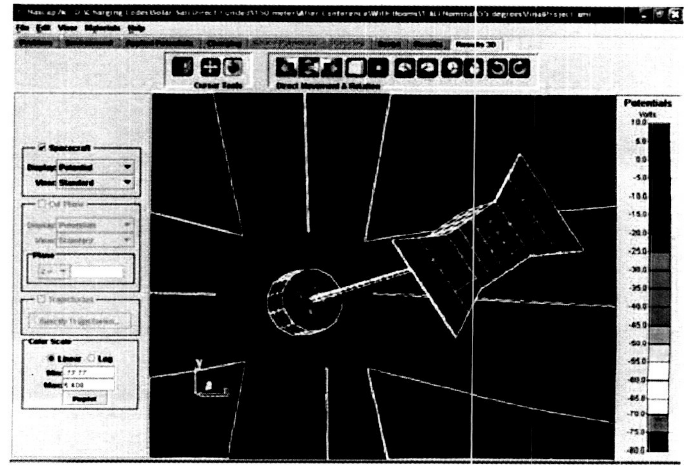


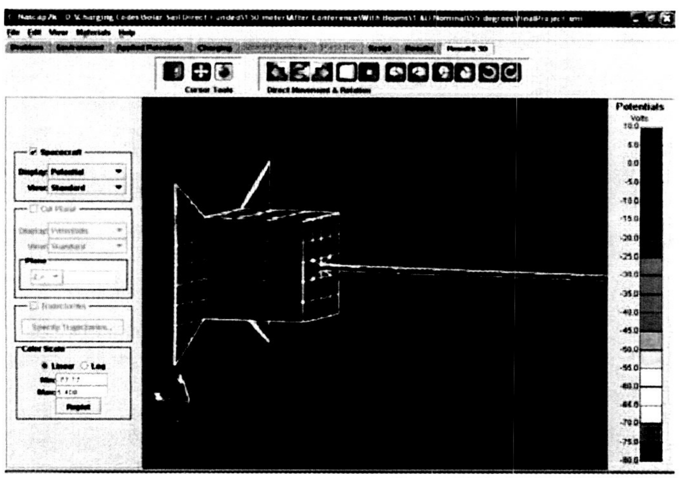


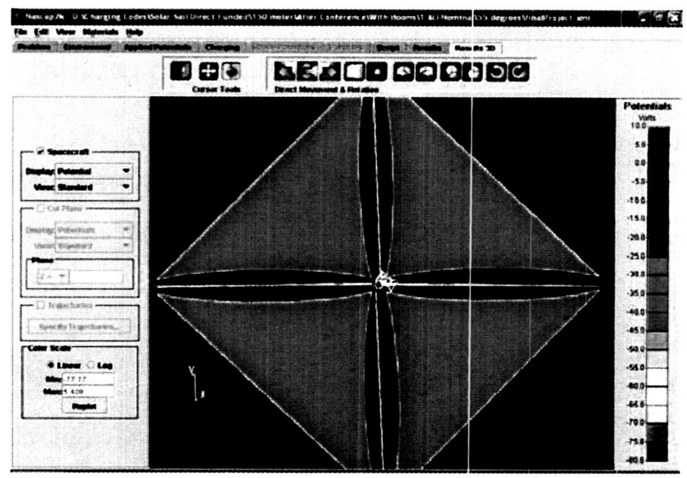


1 AU Environment 1, Insulating Back – 55 degrees

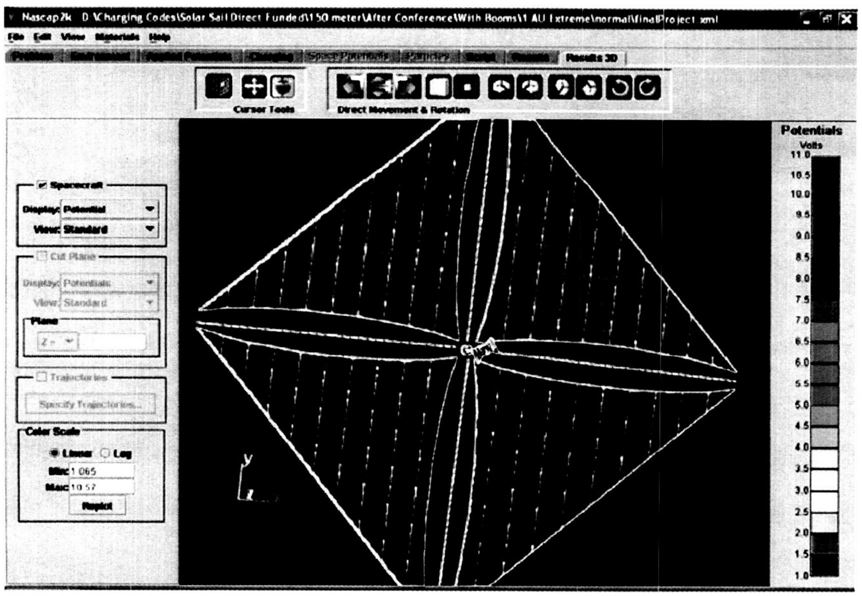


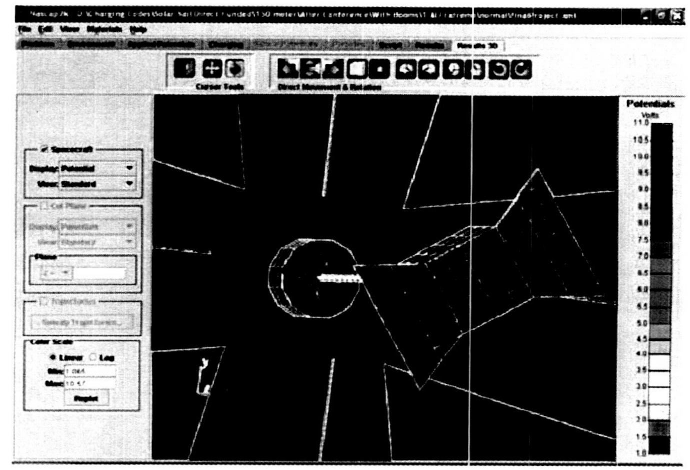


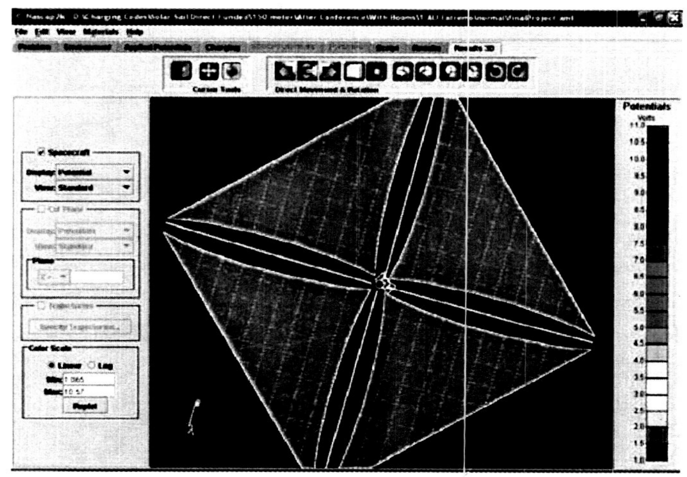




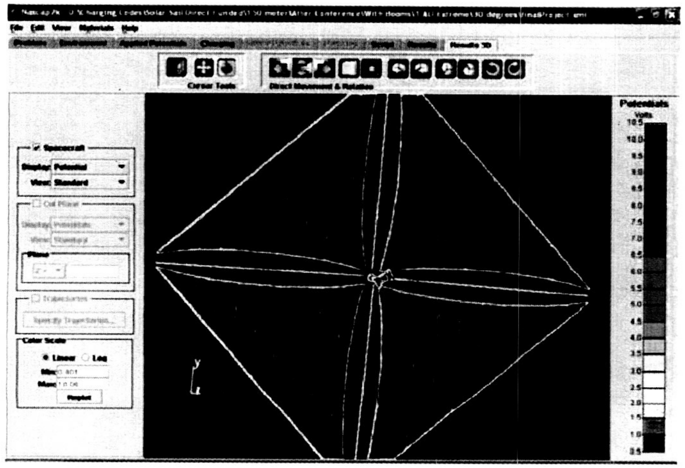
1 AU Environment 2, Insulating Back - normal

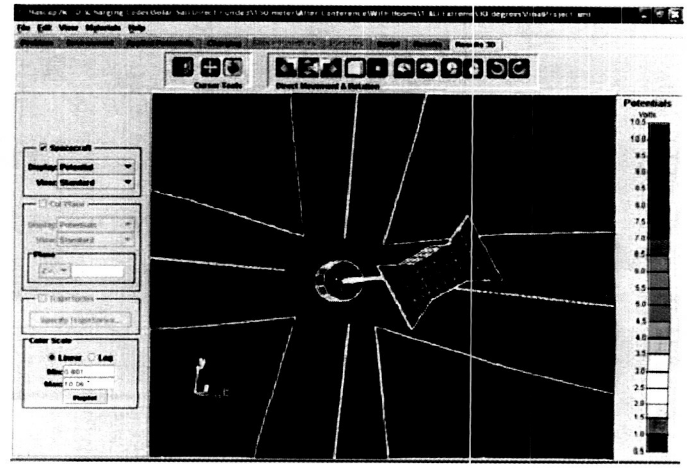


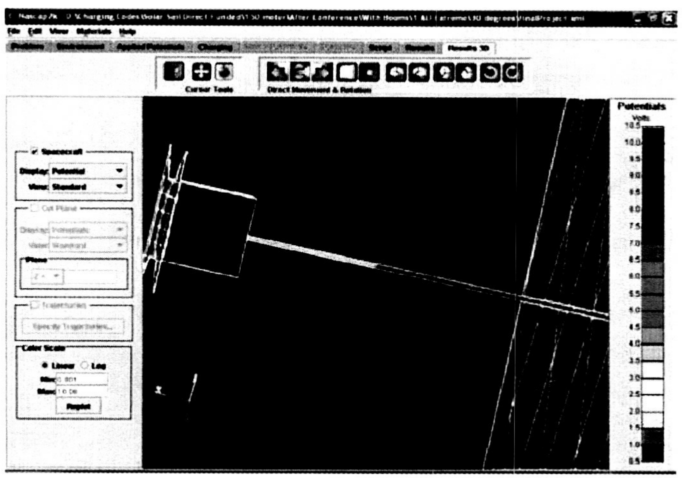


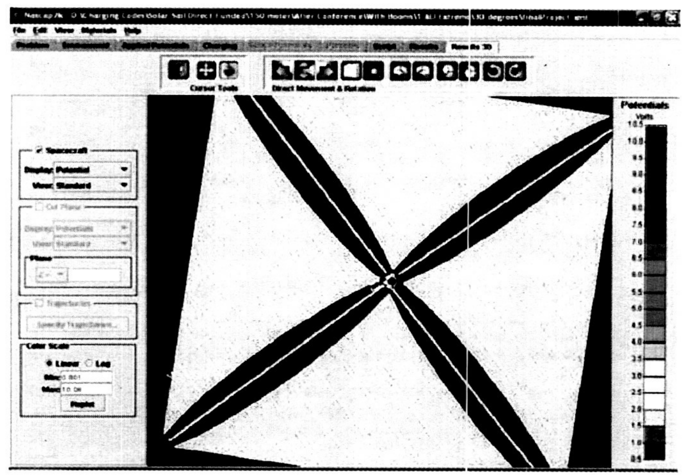


1 AU Environment 2, Insulating Back – 30 degrees

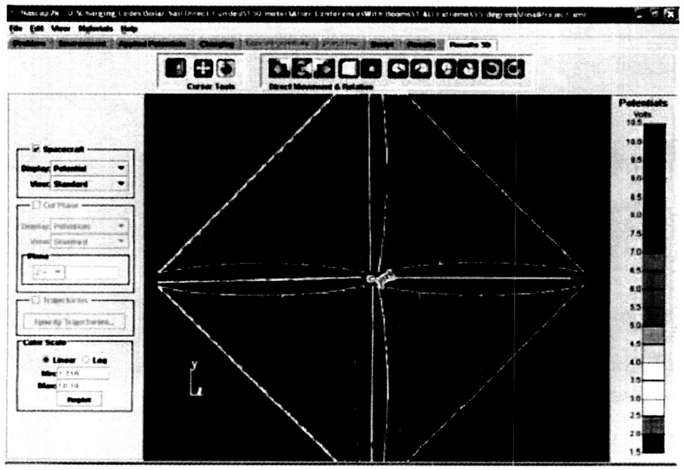


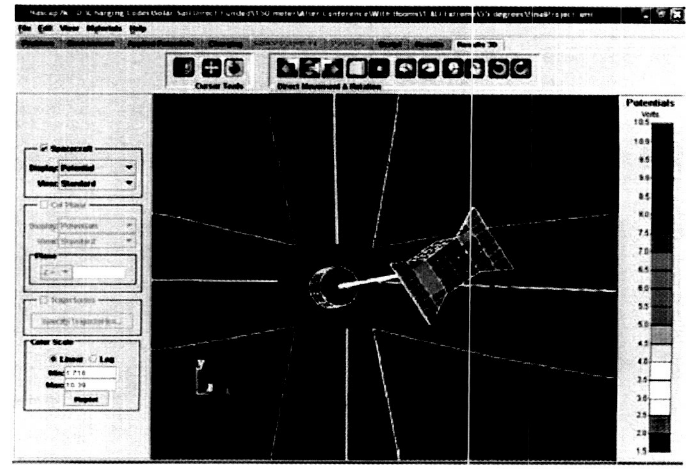


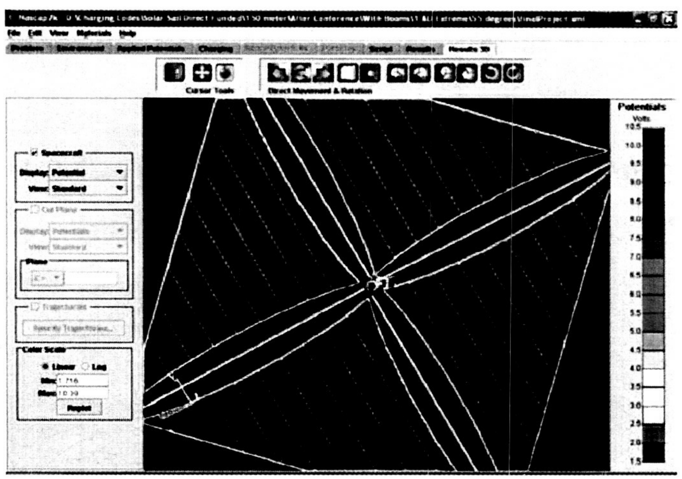


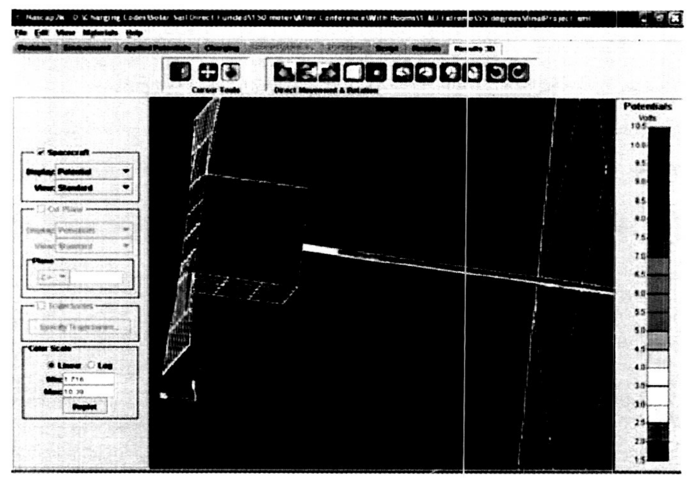


1 AU Environment 2, Insulating Back – 55 degrees









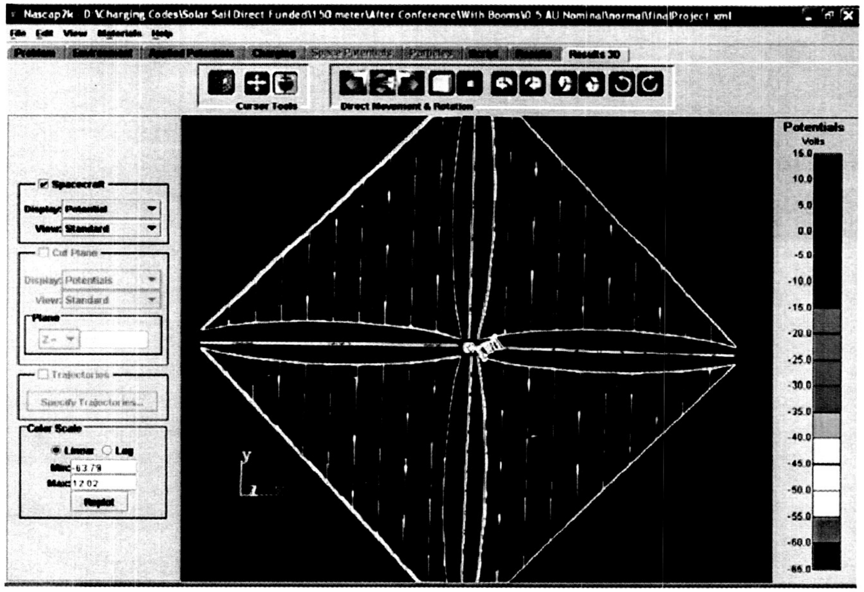
Resulting Surface Potentials – 1AU

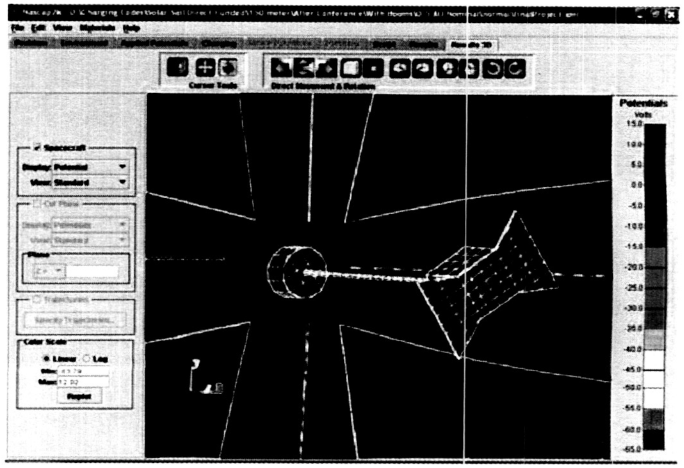
Environment		EN1				EN2	
Sail back	Insulating	Insulating	Conducting	Insulating	Insulating	Insulating	Insulating
Angle	Normal	30°	30°	55°	Normal	30°	55°
Exposed Conductor	6.684	6.315	5.104	5.349	10.57	9.9	8.13
Sail back	-42.45	-42.46	5.104	-42.48	1.92	1.89	1.72
Solar array	4.648 to 6.538	3.347 to 5.2	5.104 to 6.056	3.223 to 5.148	8.2 to 9.09	8.42 to 9.76	6.72 to 8.24
Boom/sunlight		-77.75	-4.741 to -77.80	-4.019 to -77.77		1.65 to 7.04	3.12 to 8.83
Boom/eclipse	-77.75	-42.46 to -77.75	-19.98 to -77.80	-77.77	1.69	1.65	3.12
Peak Differential Across Sail	6.684	6.315	5.104	5.349	10.57	9.9	8.13

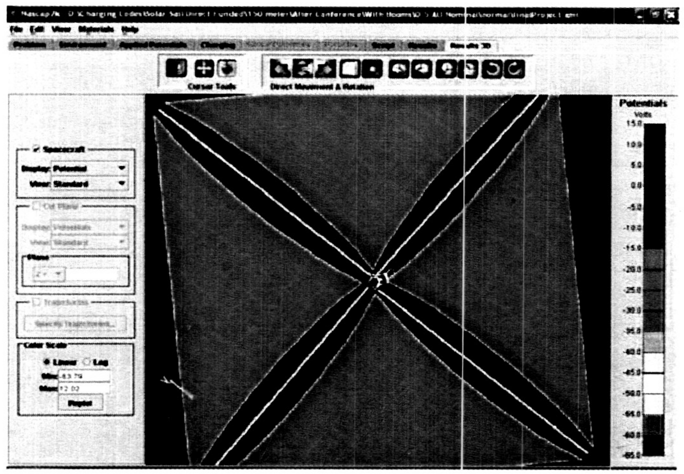
Charging time was to equilibrium

As used in the 1 AU and ½ AU "Environment 2" charging cases, high temperature (~50 eV) solar wind environment can be non-charging as, on average, each incident electron generates more than one secondary.

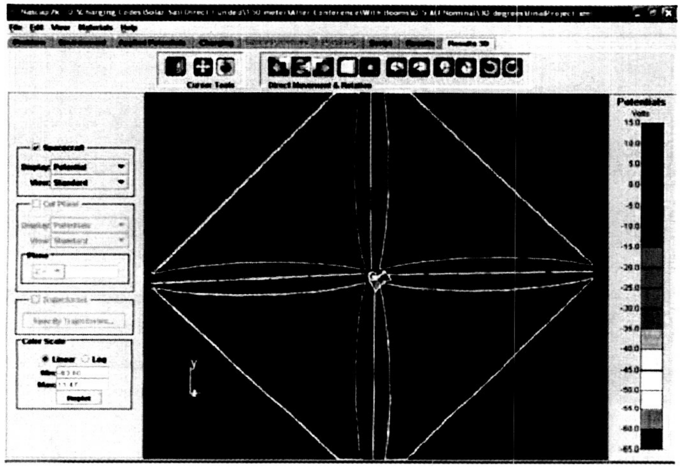
½ AU Environment 1, Insulating Back - normal

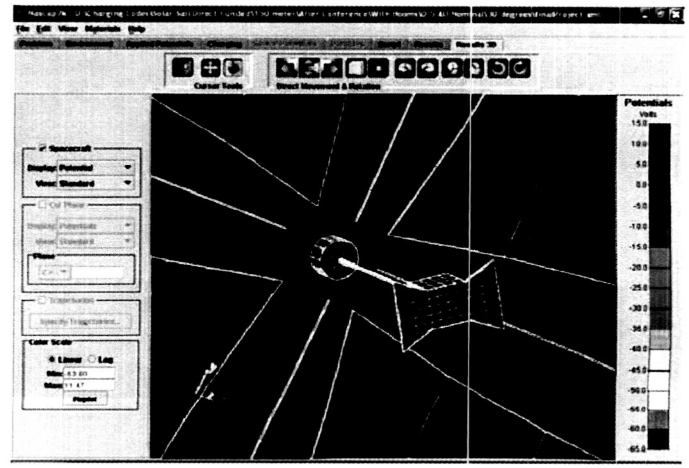


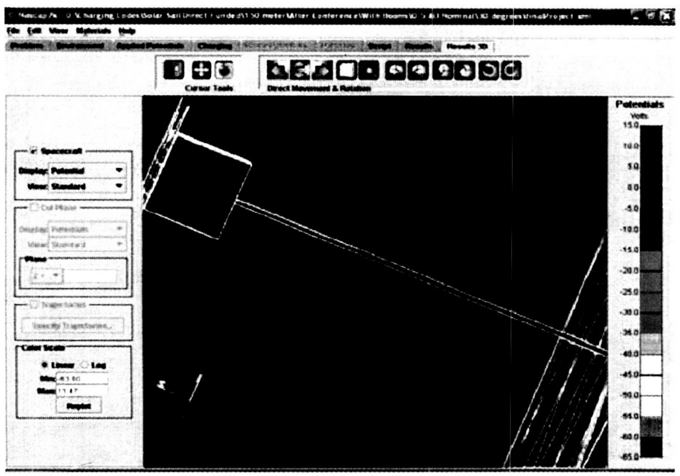


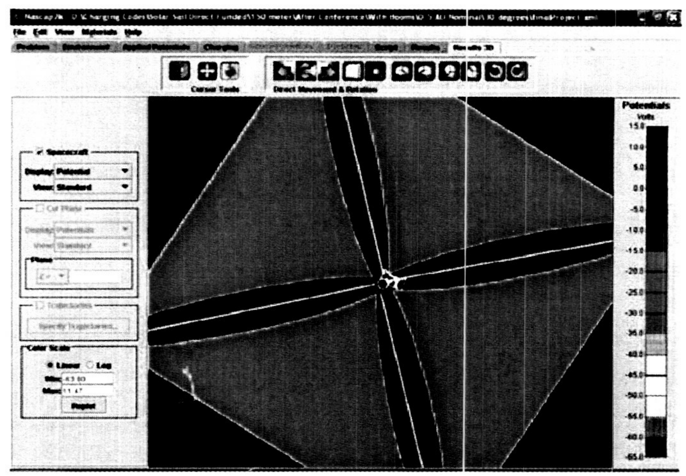


½ AU Environment 1, Insulating Back – 30 degrees









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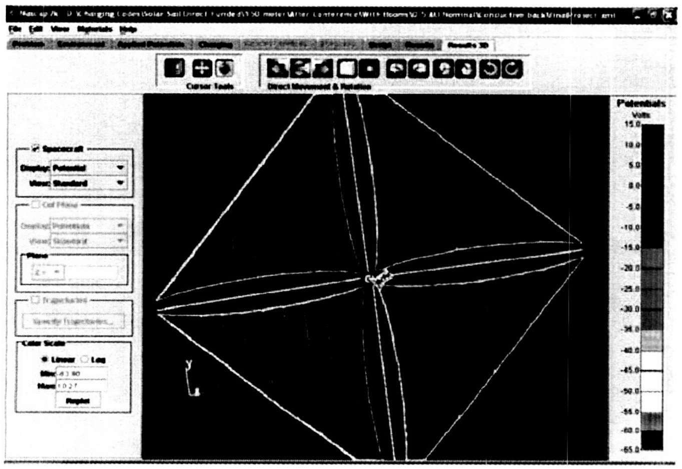
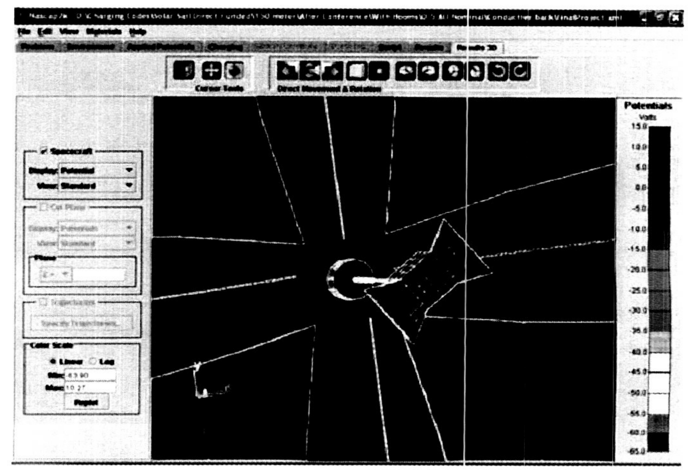
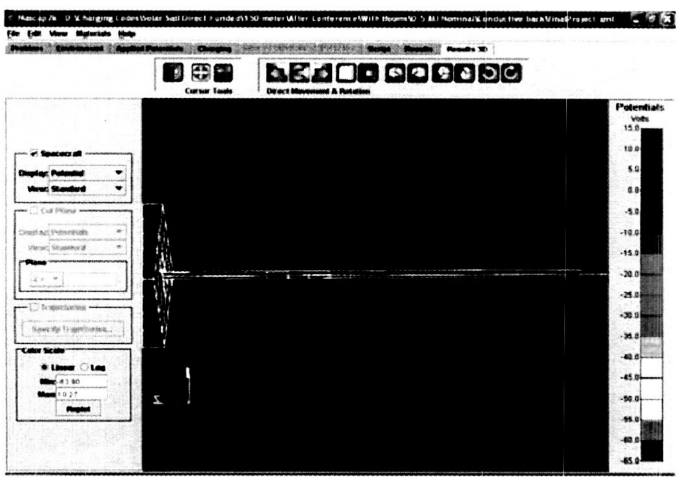
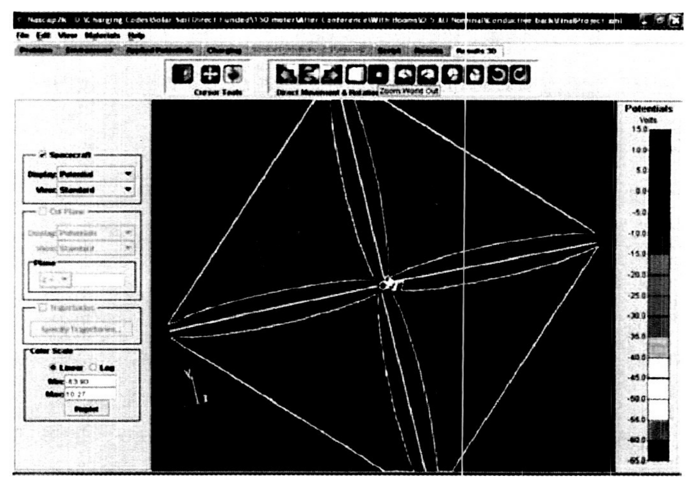
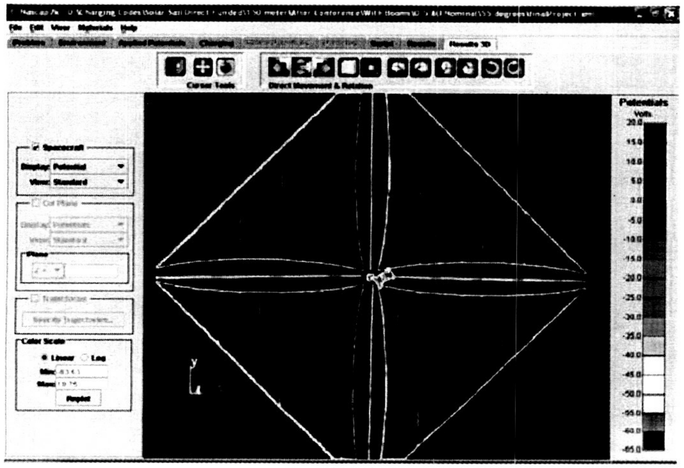


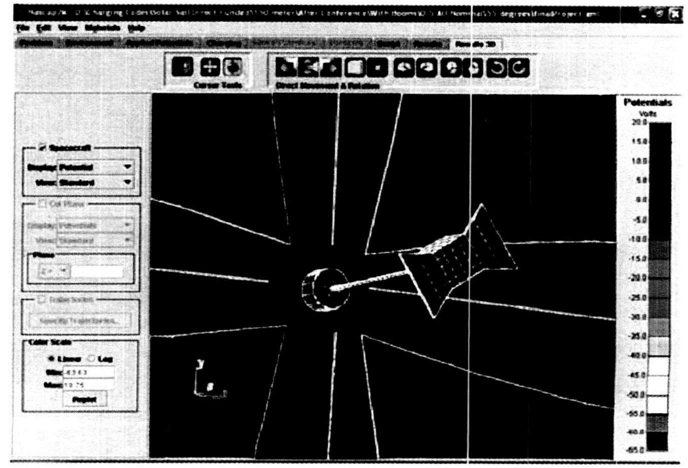


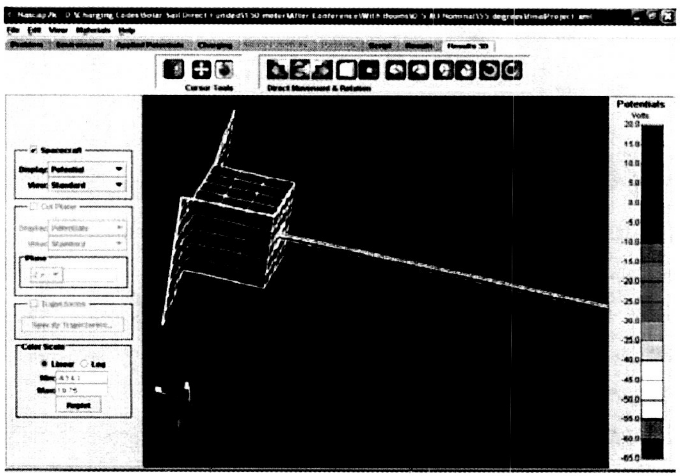


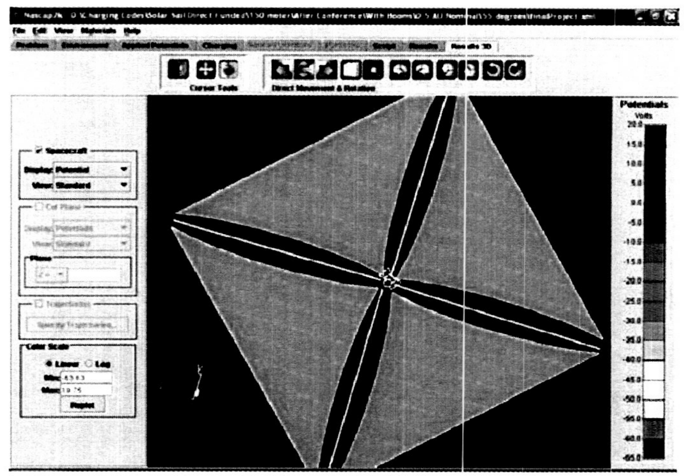


½ AU Environment 1, Insulating Back – 55 degrees

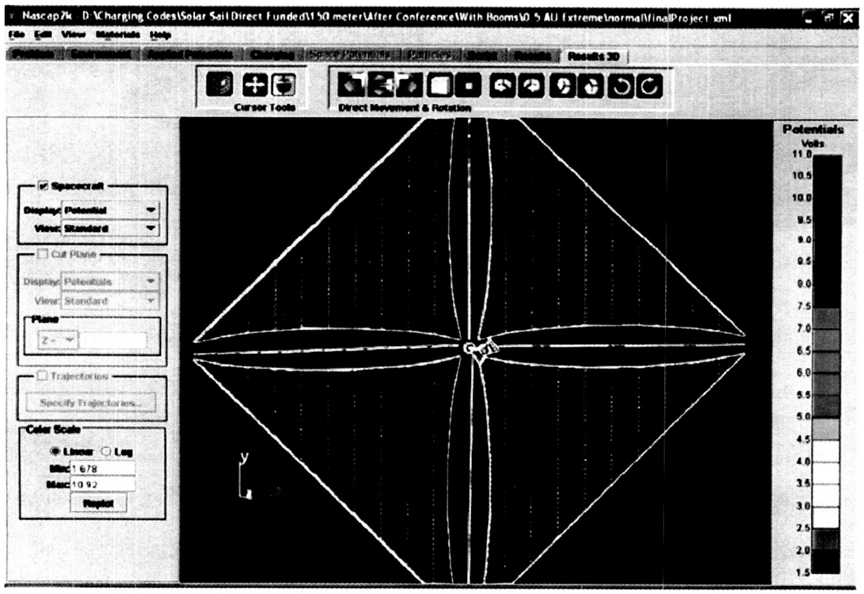


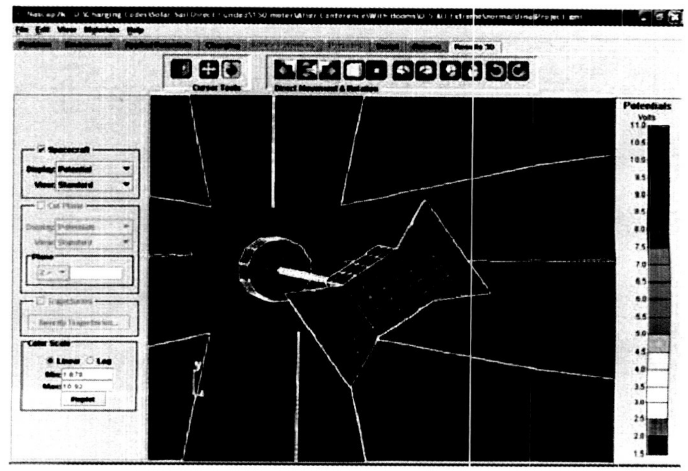


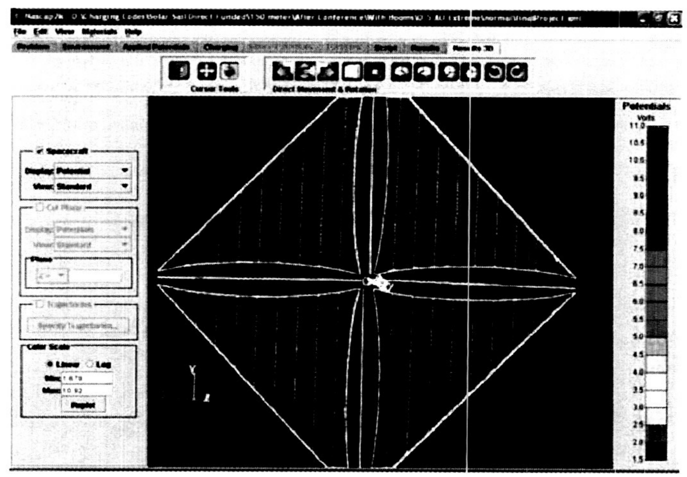




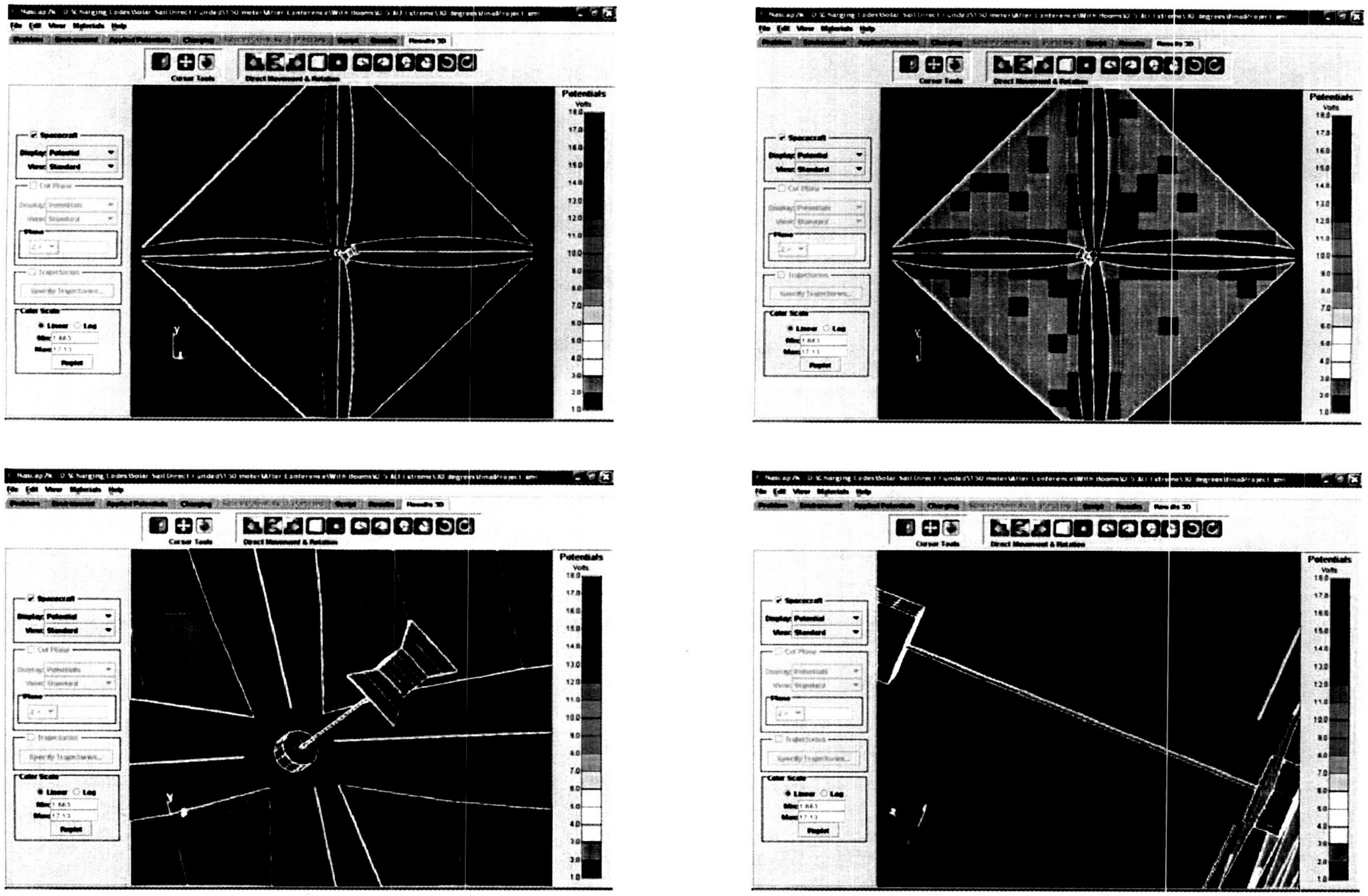
½ AU Environment 2, Insulating Back – normal



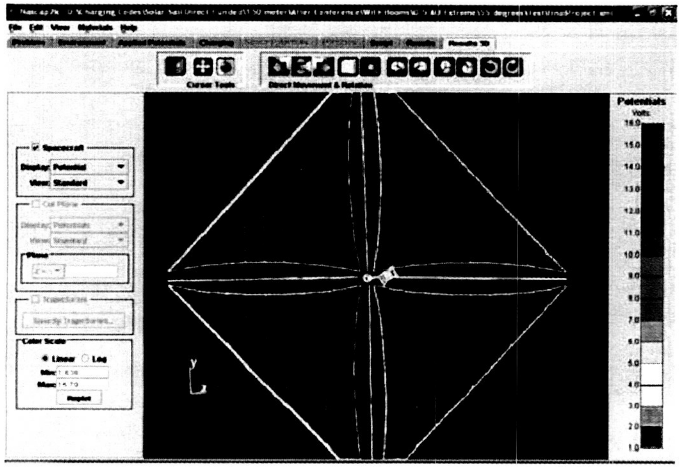
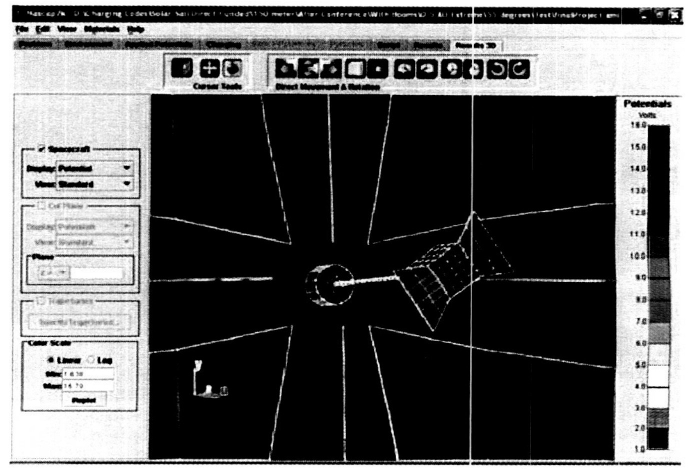
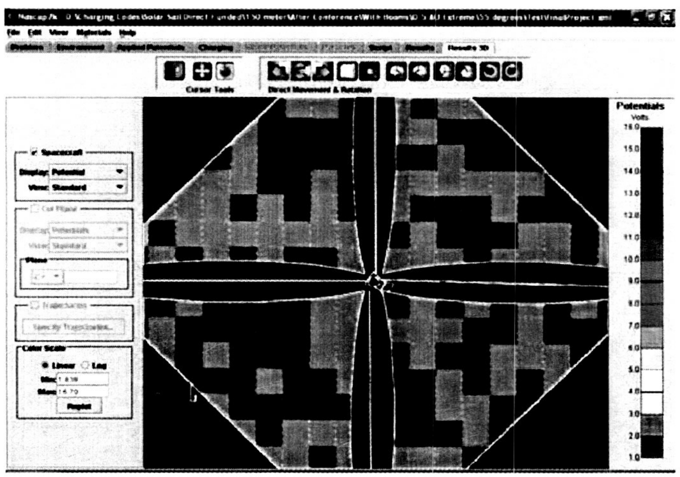
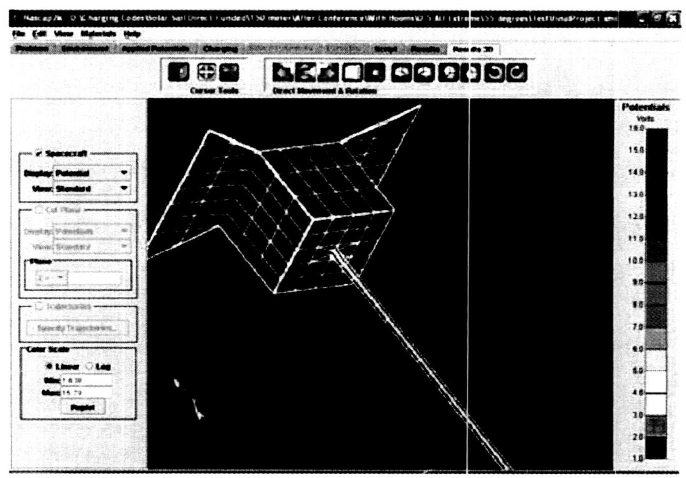




½ AU Environment 2, Insulating Back – 30 degrees



½ AU Environment 2, Insulating Back – 55 degrees

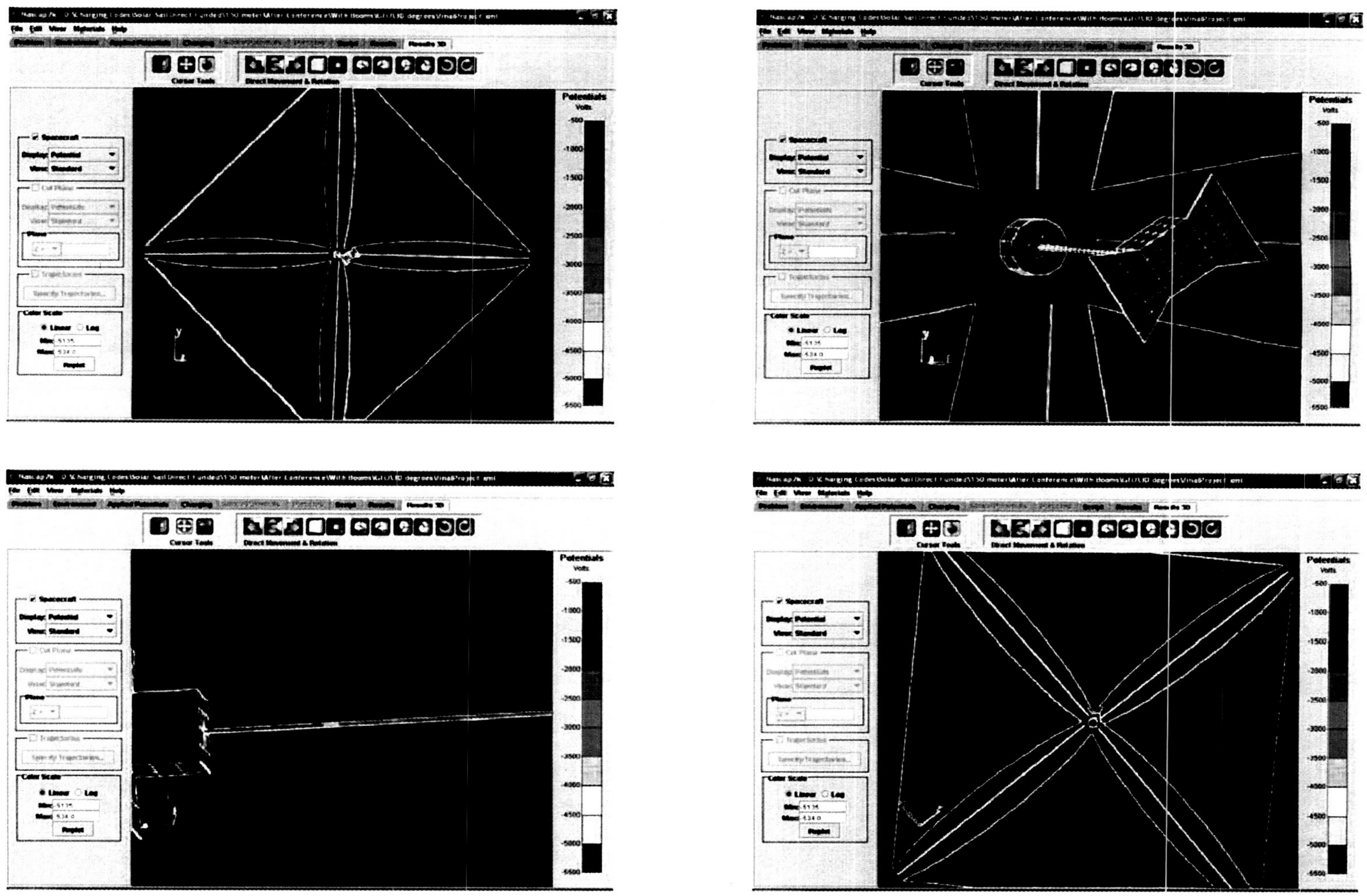





Resulting Surface Potentials – ½ AU

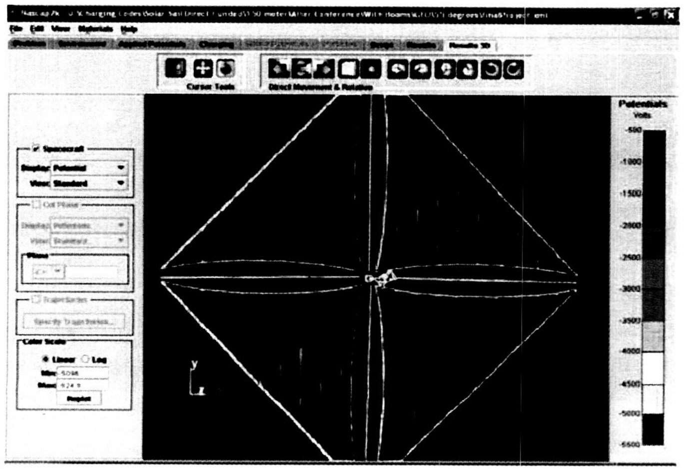
Environment		EN1				EN2	
Sail back	Insulating	Insulating	Conducting	Insulating	Insulating	Insulating	Insulating
Angle	Normal	30°	30°	55°	Normal	30°	55°
Exposed Conductor	12.02	11.47	9.834	19.75	10.92	17.13	15.79
Sail back	-30.35	-30.38	9.834	-30.15	1.93	1.66 to 2.4	1.64 to 2.56
Solar array	11.78 to 11.89	10.12 to 10.31	9.943 to 10.27	17.05 to 17.37	8.7 to 10.43	12.55 to 13.62	10.86 to 12.37
Boom/s[redacted]		2.9 to -63.80	-63.90 to 2.094	13.04 to -63.63		9.89	10.48
Boom/eclipse	-63.79	-63.80	-63.90	-63.63	2.3	1.99	1.87
Peak Differential Across Sail	12.02	11.47	9.834	19.75	10.92	17.13	15.79

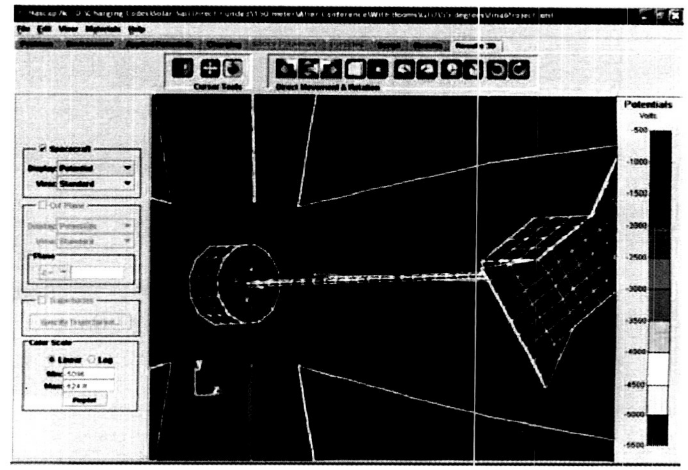
Charging time was to equilibrium

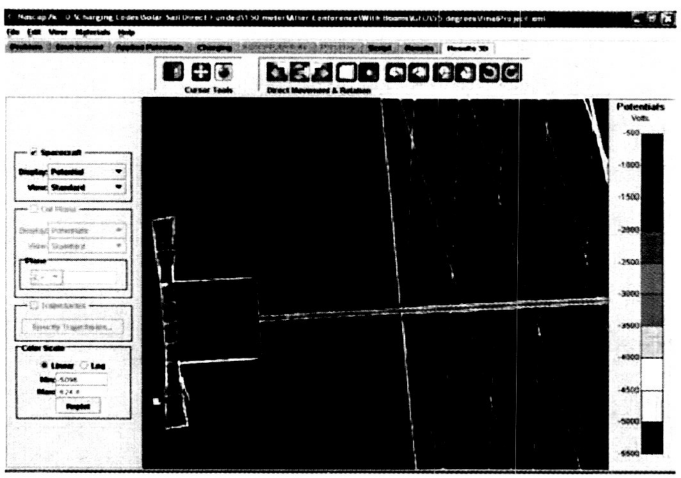
GEO Charging Analysis, Insulating Back – 30 degrees

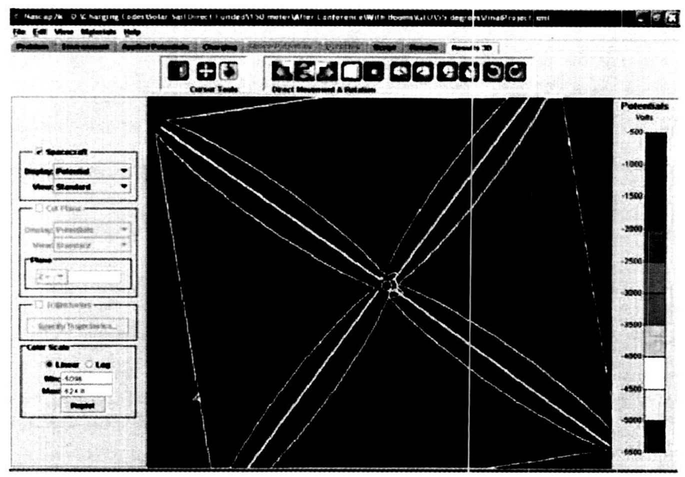


GEO Charging Analysis, Insulating Back – 55 degrees

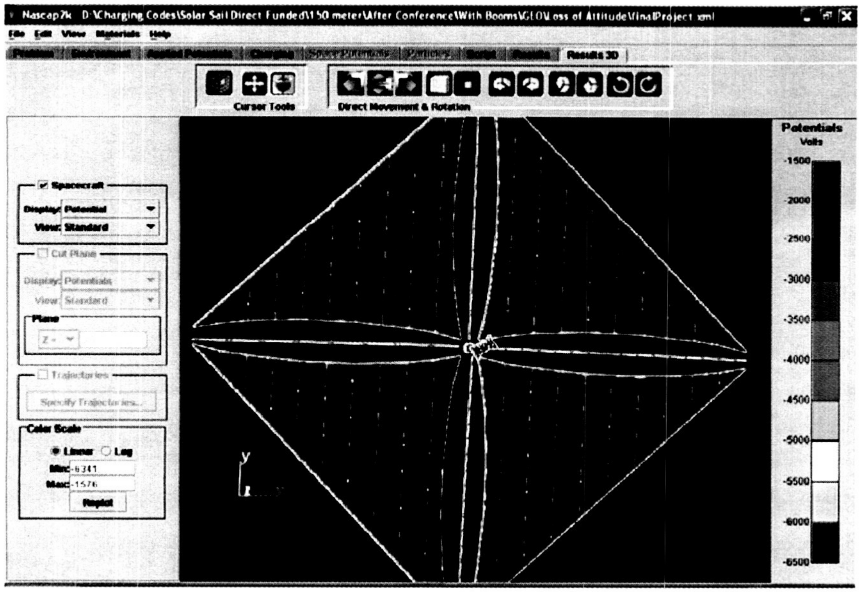


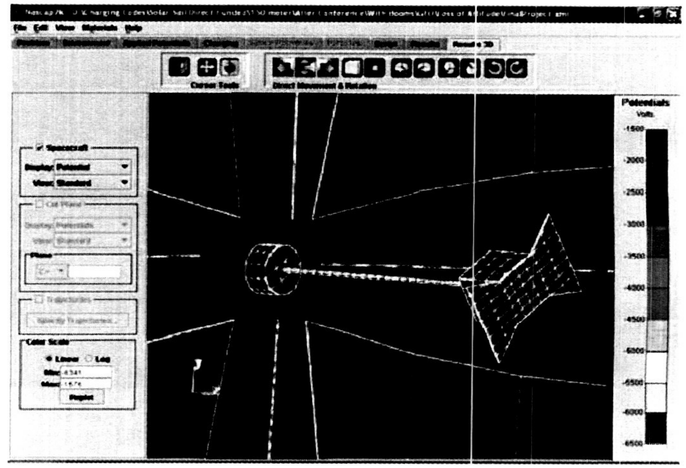


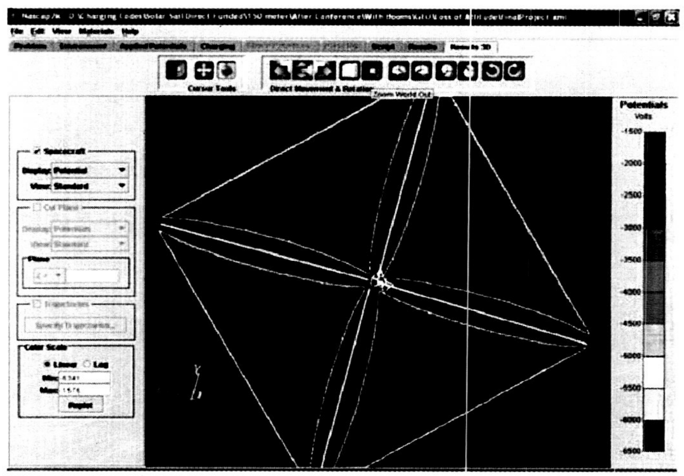




GEO Charging Analysis, Insulating Back – loss of attitude control







Resulting Surface Potentials – GEO

Environment		90% worst case	
Sail back	Insulating	Insulating	Insulating
Angle	30°	55°	Loss of Attitude Control
Exposed Conductor	-534	-624.8	-2021
Sail back	-764.3	-848.4	-1726 to -2326
Solar array	-599 to-676	-625 to -750	-2016 to -2039
Boom/sunlight	-1220 to -5135	-1292 to -5096	
Boom/eclipse	-5135	-5096	-6341
Peak Differential Across Sail	-534	-624.8	-2021
Differential			

Charging time was 15 minutes

Conclusions

- In the solar wind, differential potentials of many tens of volts can develop through a solar sail with an insulating back.
- In a geosynchronous substorm environment, kilovolt potentials can develop.
- The highest potentials developed on the insulating support structures.
- An equal potential spacecraft would minimize small discharges which could damage the thin film sail.
- Solar sail designs should minimize the use of dielectrics and floating conductors.

Electrostatic Interactions Issues Not Addressed

- Will the thin film support the surface current density?
- For large objects, electron wake may be important.
- What about charge deposition in the sail support structure, particularly in geosynchronous orbit?
- What is the effect of a change in overall conductivity due to other environments effects such as UV radiation and meteoroids?
- Radiation induced conductivity?